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Risk Assessment as a Framework for Decisions on Research and Data Collection for Nuclear Waste Repositories with Application to Carbon Sequestration Monitoring

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Abstract

The risk assessment approach has been applied to support numerous radioactive waste management activities over the last 30 years. A risk assessment methodology provides a solid and readily adaptable framework for evaluating the risks of CO_2 sequestration in geologic formations to prioritize research, data collection, and monitoring schemes. This paper reviews the tasks of a risk assessment, and provides a few examples related to each task. This paper then describes an application of sensitivity analysis to identify important parameters to reduce the uncertainty in the performance of a geologic repository for radioactive waste repository, which because of importance of the geologic barrier, is similar to CO_2 sequestration. The paper ends with a simple stochastic analysis of idealized CO_2 sequestration site with a leaking abandoned well and a set of monitoring wells in an aquifer above the CO_2 sequestration unit in order to evaluate the efficacy of monitoring wells to detect adverse leakage.

Introduction

Risk assessment provides a framework for placing information in context. Over the last three decades, the United States has applied risk assessment to key decisions concerning radioactive waste disposal. During this same period, risk concepts have been applied to nuclear reactors, nuclear fuel storage and transportation systems, and critical infrastructure such as national treasures, dams, and water supplies. A repository for radioactive waste disposal is conceptually similar to CO2 sequestration in that the geology is providing an important isolation function. Furthermore, the heterogeneous and uncertain geology must be characterized to reduce uncertainty and, thereby, develop a general understanding of its structure and behavior as a disposal system, unlike an engineered barrier. Similar to radioactive waste disposal, the extent of characterization necessary to adequately understand behavior of the geologic system will be an important unknown in any CO_2 sequestration project. Using a risk framework as the hub for decisions related to CO_2 sequestration will aid in decisions on research and data collection priorities for characterizing the site. The risk framework can also be used to evaluate monitoring schemes. A qualitative benefit of adopting a risk framework is that it will help the CO_2 sequestration community develop a sensible regulatory framework. We elaborate upon these points below.

Risk Assessment Definitions

Risk assessment is a type of policy analysis of what can go wrong in human affairs, in which the current state of scientific and technological knowledge is made accessible to society as input to risk management decisions, with time and resource constraints specified by the policy decision makers. Although risk has several connotations (if not denotations) inside and outside the profession of risk analysis, *risk* is generally used in this paper to express some measure that combines "the gravity of harm" to something valued by society and "the probability of the event." Frequently, within the risk profession, the measure of risk is the expected value of the consequence, e.g., probability times consequence based on average values, as used in simple annuity analysis. For financial investments, the measure is often the variance of the return on investment. For situations with large uncertainty, such as disposal of radioactive wastes, the measure of risk is the entire distribution of possible consequences.

For risk assessments of nuclear facilities, two specific terms are used: *probabilistic risk assessment* (PRA) and *performance assessment* (PA). *Probabilistic risk assessment* denotes a risk assessment that specifically evaluates the uncertainty of knowledge from various sources in the analysis. Although not limited to such usage in this paper, the word also frequently connotes a risk assessment of risk to health over a human lifetime from an engineered system such as a nuclear power plant, where failures are short-term events (in relation to the life of the system).

Generally, a *Performance assessment* (PA) is the *process* of assessing whether a *system* meets a set of *performance criteria*. The *system* may be a deep, geologic disposal system for radioactive waste in salt or CO_2 in a brine aquifer. The *performance criteria* are long-term measures specified by U.S. Environmental Protection Agency (EPA) for radioactive waste disposal or yet to be promulgated measures for CO_2 sequestration. The assessment *process* is through mathematical modeling. Given this definition and assuming the performance criteria are risk-based and uncertainties are evaluated, PA and PRA are synonymous terms within the United States. However, a *performance assessment* usually connotes a risk assessment to illustrate possible behavior over geologic time scales of a radioactive waste disposal system composed of both and natural and engineered components (e.g., formation stratigraphy and abandoned wells). In such a system, the natural components evolve rather than fail, as in an engineered system.

Paper Organization

This paper first reviews the tasks of a risk assessment, and provides a few examples related to each task, to qualitatively demonstrate its applicability. A performance assessment for radioactive waste disposal has many of the necessary attributes of risk assessment for CO_2 sequestration in a geologic formation. Thus, this paper then describes an application of sensitivity analysis to identify important parameters to reduce the uncertainty in the performance for the Waste Isolation Pilot Plant (WIPP), a repository for disposal of defense waste contaminated with transuranic (TRU) radioisotopes in southeastern New Mexico. The paper ends with a simple stochastic analysis of an idealized CO_2 sequestration site with a leaking abandoned well and a set of monitoring wells in an aquifer above the CO_2 sequestration unit to evaluate the efficacy of monitoring wells to detect adverse leakage.

Risk Assessment Framework

Risk Assessment Tasks

There is subtle but important distinction between *prediction* of an event and *assessing the risk* of a future event. Predicting an event such as leakage of CO_2 from a storage formation at an abandoned wellbore requires identifying when the leakage will occur, where the leakage will occur (the exact location out of many boreholes), and the amount of leakage. The usefulness of the prediction depends on the accuracy in specifying the leakage event (e.g., when, where, and how much). In contrast, assessing the risk of leakage requires estimating the probability of leakage at wells penetrating the storage formation and estimating the effect of this leakage. A prediction of when, where, and how much leakage is not required. The process of modeling is to develop information on the consequences of the leakage based on scientific knowledge of the type of leakage under consideration and perhaps pertinent physical processes in wellbore leakage, and estimate of the probability of the event. The tasks of the risk assessment are to provide the underlying scientific information necessary to estimate a range of consequences and corresponding probabilities.

In general, a probabilistic risk assessment of a disposal system for radioactive waste or CO_2 comprises up to seven tasks that form a framework for organizing information (Rechard 1999): (0) identify appropriate measures of risk and corresponding risk limits; (1) define and characterize the disposal system geologic barrier and agents acting on the system; (2) identify sources of hazards through selection of features, events, and processes (FEPs) and form scenarios of alternative behavior from these FEPs; (3) quantify uncertainty in consequence estimates (often through definition of uncertainty in modeling parameters and uncertainty in model forms using probability distributions) and evaluate probability of scenarios though development of probability models; (4) evaluate the consequences usually quantitatively through construction of system exposure models to simulate relevant geologic, hydrologic, and geochemical processes; (5) combine the evaluated consequences and probabilities and compare with risk limits; and (6) perform sensitivity to identify the parameters and model form whose uncertainty most explains the variance in the performance measure to gain further understanding.

The seven steps provide answers to three fundamental questions of risk assessment (Kaplan and Garrick 1981): What hazards can occur? What is the probability of these hazards? What are the consequences potentially caused by these hazards? As with any policy process, the boundaries between tasks may overlap. That is, the elements that make up the tasks can be performed simultaneously with other elements and not necessarily in the sequence enumerated. Moreover, the process of performing the specific task is more continuous than discrete (Figure 1).

Task 1: Identify Performance Measures

As outlined above, a risk framework starts with an identification of important hazards, followed by selection of indicators for the hazards, followed by specification of measures for the indicators. In a general sense, requirements could be developed to capture safety, economic, social and other relevant issues. Herein, we focus on safety. The regulations for radioactive waste disposal are unique in that they require (Ewing et al. 1999; Rechard 1999) (1) numerical models to evaluate system acceptability, and (2) quantitative treatment of uncertainty. Furthermore, the limits of release are expressed probabilistically (i.e., the entire distribution is regulated not just the mean or variance).

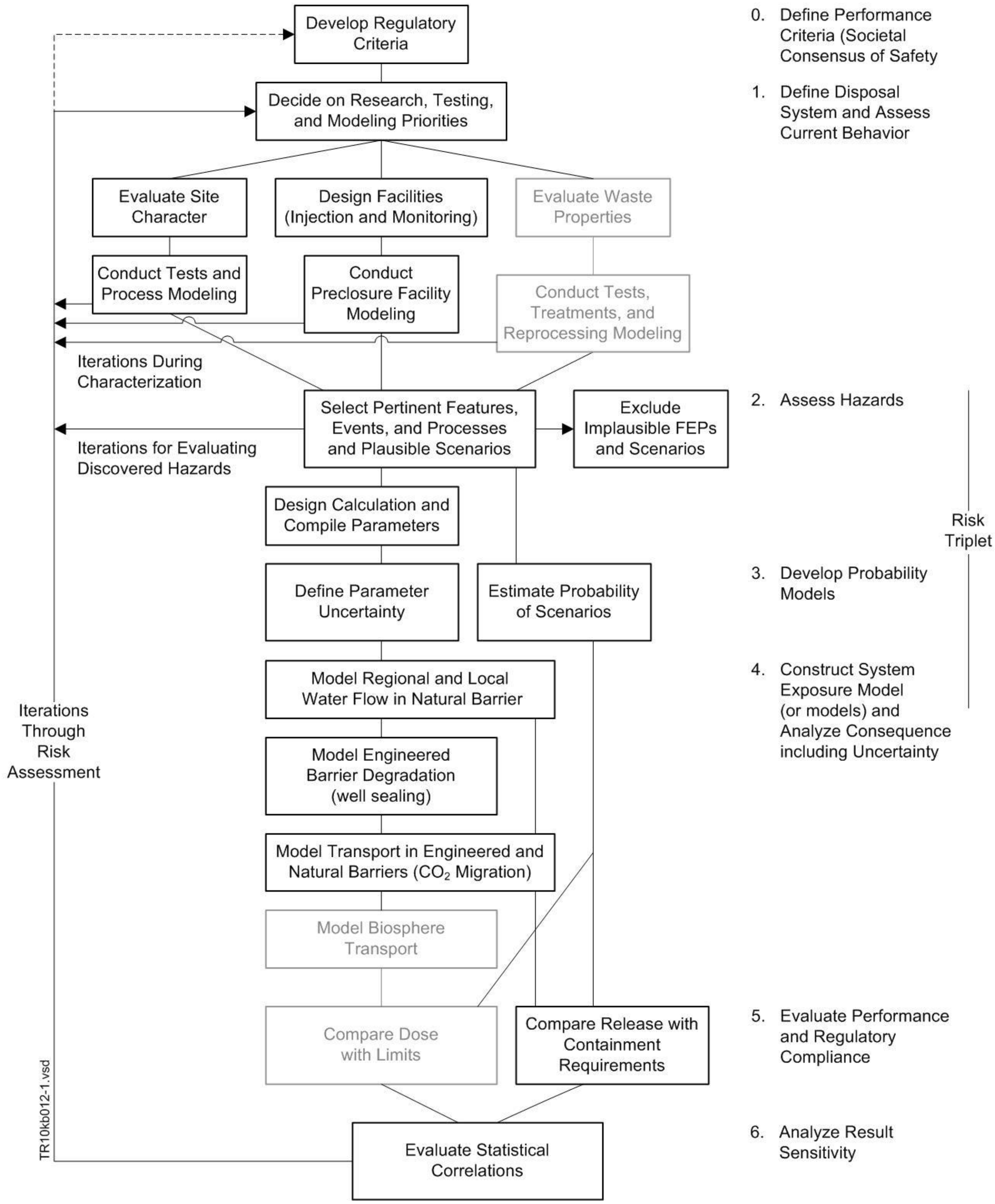

Figure 1. Elements for a risk assessment to assess efficacy of radioactive waste disposal with similar elements for CO_2 sequestration emphasized (Rechard 1996, Figure 1.2-1).

Although CO_2 injection into reservoirs has occurred since the early 1970s for tertiary oil recovery, CO_2 injection into formations is being considered on a much larger scale. Hence, much of what must occur now for CO_2 sequestration from a risk regulatory standpoint is the identification of hazards, selection of indicators for those hazards, defining measures for those indicators, and finally, specifying appropriate limits on those measures. Conceivably, two types of hazards will be present. The first hazard is the potential to damage other reservoirs, either fresh water or hydrocarbon. The second hazard is the ability to retain the CO_2 for 500 yr or so, and, thus, meet a fiduciary obligation that can be traded in a cap and trade market. A government entity will be responsible for mitigating both types of hazards, although the financial industry will be heavily involved in the later hazard. Also, the extent that the government promotes and provides incentives for this activity will also depend upon the feasibility and ability of CO_2 sequestration to retain substantial quantities of CO2 at reasonable cost.

Another aspect of the first task is development of selection criteria, based on the regulatory criteria, that specify desirable aspects such as minimum depths, types of reservoir (e.g., brine or abandoned hydrocarbon), reservoir size, proximity to infrastructure, proximity to population centers.

Task 2: Characterize Site

The second task of a risk assessment is the characterization of the disposal system to ensure that it is capable of retaining sufficient quantities of CO_2. Site characterization will likely progress through two study phases: (1) non-intrusive evaluation and literature search for site selection; (2) exploration from the surface for evaluating repository feasibility. Experience with characterizing the WIPP site showed that once a site was selected for detailed evaluation, the focus moved to uncertainties in properties and the question became one of whether enough work had been done to resolve them. Program managers can have difficulty assessing whether a broad set of scientific activities needs to be done. To counteract the tendency to expand site evaluation activities beyond what is necessary for siting and licensing decisions, use of risk assessment to prioritize data collection needs has proved useful both in the US and internationally, and an example is provided in the next section.

Task 3: Identify Hazards

The third task is hazard identification at a particular site. Once a reasonably good site has been selected, the focus of the risk analysis is on what can go wrong with a geologic disposal system. Any type of analysis must decide what features (such as fractures and faults in the host strata), events (short-term phenomena such as inadvertent drilling into the reservoir), and processes to model (long-term phenomena such as CO_2 migration through fractures); however, the decisions are typically based on the experience of the modeler and somewhat ad hoc. Because a risk assessment for a repository for radioactive waste was used in the licensing arena to test compliance, the identification and selection of features, events, and processes (FEPs) was formal.

Identification of features, events, and processes (FEPs) that could disrupt the ability of the disposal system to contain CO_2 will have begun in a generic sense during the development of regulations. However, after selection of a site, FEPs specific to the site will have to be identified and various scenarios for CO_2 migrating out of the reservoir developed. The comprehensive FEPs lists developed for the radioactive waste disposal systems may provide a useful starting point and generic lists specific to CO_2 sequestration are being developed as part of some research programs. The FEPs are strung together to form scenarios of how CO_2 may escape prematurely from the reservoir.

Task 4: Define Uncertainty in Scenarios and Model Parameters

The fourth task is evaluating the uncertainty associated with scenarios and underlying parameters of the models. As discussed above, it is the explicit evaluation of uncertainty that set the regulatory requirements for radioactive waste risk assessments apart from other types of risk assessments. A nominal scenario with rather slow migration of CO_2 out of the reservoir through minor leaks in penetrating wells and dissipation laterally will have the highest probability. However, more rare events of major leaks may need to be evaluated. As an example, the disruptive events initiating migration of radioisotopes were modeled as Poisson processes at WIPP.

Evaluating uncertainty in model parameters is also important and was a major task at the WIPP (Rechard and Martin 2005a; 2005b). A managed process was used to consistently develop probability distributions for parameters representing uncertainty in four preliminary and the final 1996 PA for the WIPP. A parameter development team assigned 67 probability density functions (PDFs) in the 1989 WIPP PA and eventually 236 PDFs in the 1996 WIPP PA. In the five iterative PAs conducted, the most commonly used distributions were the uniform PDF and piecewise-uniform PDF. Other distributions used included the truncated normal, truncated Student-*t*, and triangular PDFs. In a few instances, a discrete delta, beta, and exponential PDF were also used.

Task 5: Build Models and Evaluate Consequences

The fifth task is evaluating the consequences of scenarios proposed such as the extent of leakage and the damage to other reservoirs. Modeling has two purposes in a safety case for a repository: (1) demonstrate adequate understanding of the current system based on information collected during site characterization, and (2) assess performance in order to compare with regulatory criteria. As already noted, the purpose of the modeling is not prediction but rather to develop a body of plausible futures to produce a record from which to estimate the probability of extreme events occurring. It is a means to build confidence that the disposal system will behave adequately in the future whatever the real situation.

Task 6: Evaluate Parameters and Model Form Sensitivity

The sixth task is a sensitivity analysis, which analyzes the effects of changes in parameters or in model form on mathematical model predictions of the disposal system behavior. The four principal purposes of a sensitivity analysis are (Rechard 1996): (1) to gain understanding and insight about the disposal system, (2) to help verify the correctness of the calculations, (3) to evaluate the influence of various options, and (4) to determine where more knowledge is required to provide input on decisions on how to allocate resources to collect data on parameters and improve model forms that most influence the results, based on what is already known about the disposal system, in order to improve understanding and to better refine the risk assessment in future iterations.

Several techniques can be used in sensitivity analysis. The simplest method is a *ceteris paribus* sensitivity analysis whereby a limited number of parameters or model forms are varied one at time. This method is most appropriate for evaluating the influence of differences in controversial alternative conceptual models where the independence of the options and alternative models can be reasonably assured or to evaluate options such as monitoring schemes.

In many instances for material property parameters related to consequence models, the interaction of a parameter changes with other parameters must be evaluated. In the example of CO_2 sequestration presented below, plots of uncertain parameters against results are presented. Often, the number of parameters to examine is so large that detailed visualization is difficult and statistical methods must also be applied whereby a regression model is developed.

WIPP Project Guidance from Sensitivity Analyses

Background on Waste Isolation Pilot Plant

The search for permanent disposal for radioactive waste began in 1955 when the Atomic Energy Commission (AEC) asked the National Research Council of the National Academy of Science and Engineering (NAS) to examine the disposal issue. In 1957, the NAS reported that deep geologic disposal in salt formations was the most promising method to explore for disposing of high-level waste (HLW) resulting from reprocessing of spent nuclear fuel (SNF) (Rechard 2000). With the positive attributes and technology available in the 1950 and 1960s, the AEC gave mined disposal in salt high priority, especially for defense-related radioactive waste.

Local citizens invited the AEC to New Mexico to consider the thick bedded salt deposits in southern New Mexico in 1972, and the search for a specific site in the Delaware basin occurred between 1973 and 1976. The site for the Waste Isolation Pilot Plant (WIPP) was characterized in support of the draft Environmental Impact Statement (EIS), which was completed in 1979.

In December 1979, Congress authorized the Department of Energy (DOE), successor to AEC, to construct the WIPP repository for disposal of defense waste contaminated with TRU radioisotopes (mostly Pu) and hazardous chemicals generated during the production of nuclear weapons. The first shaft was excavated in 1981; full construction began in 1983; and construction was substantially complete by the end of 1988. Along with construction, an underground research laboratory was deployed to the north of the disposal area.

The WIPP Project conducted a preliminary performance assessment (PA) in 1989 to demonstrate the feasibility and three performance assessments (1990, 1991, and 1992) to demonstrate the viability of the WIPP. In 1996, the certification PA and Compliance Certification Application (CCA) was completed. In 1998, the Environmental Protection Agency (EPA) certified that the WIPP disposal concept complied with its regulations. After dismissal of lawsuits, the WIPP repository received its first shipment of waste in 1999; 25 years after the area in New Mexico was first identified and 20 years after authorized by Congress. Two PAs have been run since 1996, one in 2004 and one in 2009 for recertification that is required every 5 yr,

Sensitivity Analysis at WIPP

For the WIPP Project, understanding for six general processes was necessary: (1) solubility of actinides in brine (which eventually included increased concentrations from sorption on colloidal material), (2) hydrologic transport of actinides in the overlying heterogeneous and fractured brine aquifer, (3) fluid flow in the host salt formation, (4) multiphase flow from gas generation produced by anoxic corrosion of metals and decomposition of organic material in the waste, (5) creep of salt into the excavated disposal rooms and shafts, and (6) releases from cuttings, cavings, and spallings if someone inadvertently drilled into the repository. The sensitivity analyses between 1989 and 1992 provided guidance to project managers on how to direct resources for the collection of important model parameters and improvement of model forms related to these general processes.

1989 WIPP PA

In the first WIPP PA in 1989, 67 model parameters were assigned distributions. The uncertainty in the resulting performance measure from 27 of these 67 parameters was evaluated. The five most important parameters for release of actinides through the groundwater pathway were as follows (Table 1): (1) the solubility of actinides ($S_{actinde}$); (2) time of one inadvertent human intrusion into the repository ($t_{intrude}$) (rate and multiple intrusions were not modeled in 1989); (3) the assumed permeability of the resulting but abandoned borehole from the human intrusion ($k_{\mathbf{x}\text{-}bore}$); (4) the matrix porosity of the waste ($\phi_{m\text{-}waste}$); and (5) the permeability of the waste ($k_{\mathbf{x}\text{-}waste}$).

Based on this initial sensitivity result, plans were made to focus on characterizing the uncertainty of actinide solubility through an expert elicitation by 1991 (Trauth et al. 1992). The lack of fidelity in the system model, motivated the WIPP project to add more details to model components in the next iteration in 1990 (particularly, the ability to model multiphase flow within the repository, and transport within the overlying brine aquifer in the Culebra Member of the Rustler Formation, and radioisotope releases from bringing cuttings, cavings, and spallings.

1990 WIPP PA

In the 1990 PA, the total number of model parameters increased to 217; 78 parameters were assigned distributions; and the uncertainty of 40 of these parameters was propagated through the 1990 PA. This 1990 WIPP PA also evaluated release of actinides from cuttings brought directly to the surface. Important parameters were actinide solubility ($S_{actinide}$), intrusion time ($t_{intrude}$), borehole cross-sectional area (A_{bore}), and radioisotope adsorption distribution coefficient (Kd_e) in the brine aquifer in the Culebra (which influenced actinide transport within the brine aquifer) (Table 1). Because of its importance (as represented by $t_{intrude}$), an expert elicitation panel was convened for evaluating inadvertent human intrusion in WIPP (Hora et al. 1991).

Table 1. Important parameters and project response to examine uncertainty in WIPP PAs (Rechard and Tierney 2005b).

Year	Parameter	Project Response
1989	**Groundwater pathway**	
	Solubility, actinide ($S_{actinde}$)	An expert panel was formed to evaluate radioisotope solubility in brine (Trauth et al. 1992).
	Human intrusion time ($t_{intrude}$)	Time of intrusion modeled as computational scenario and as part of simulation; also, improved model to include multiple intrusions
	Permeability, borehole ($k_{\mathbf{x}\text{-}bore}$)	
	Porosity, waste ($\phi_{m\text{-}waste}$)	Modeling of flow in repository improved using finite difference and finite element codes
	Permeability, waste ($k_{\mathbf{x}\text{-}waste}$)	
1990	**Groundwater pathway**	
	$S_{actinide}$	Funded experimental program to determine solubility in brine for use in 1991 PA; continued development of code to model actinides separately
	$t_{intrude}$	Chose to model time of intrusion as computational scenario; also, an expert elicitation panel was convened for evaluating inadvertent human intrusion in WIPP (Hora et al. 1991).
	Borehole drill diameter (d_{drill})	Began development of multiphase flow code to improve modeling of repository flow
	Partition coefficient of matrix for Pu (Kd_{Pu})	Continued development of flow and transport codes and stochastic description of permeability field
	Kd_U	
1991	**Cuttings release pathway**	
	Human intrusion rate (λ_{drill})	Continued to fund improvement in the evaluating cuttings and cavings from human intrusion
	d_{drill}	
	Groundwater pathway	
	Solubility, Pu^{IV} (S_{PuIV})	Continued funding of experimental program on actinide solubility
	S_{PuV}, S_{AmIII}, S_{UIV}, S_{UVI}	
	$k_{\mathbf{x}\text{-}bore}$	
	$k_{\mathbf{x}\text{-}halite}$	Made plans to model reduction in porosity in room from salt creep
	Kd_{Pu}, Kd_{Am}, Kd_U	
	Fracture porosity in Culebra, (ϕ_f)	Discussions begun on field tracer test to selection best conceptual model
	Fracture space in Culebra ($2B_{Culebra}$)	
	Climate amplitude factor (A_{amp})	
	Pressure in brine pocket (P_{pocket})	
1992	**Direct release pathway**	
	λ_{drill}	Because of continued importance of direct release pathway, initiated development of model to include spalling of pressurized waste into borehole and release of contaminated brine through the borehole for the CCA PA in 1996
	$k_{\mathbf{x}\text{-}bore}$	
	S_{Am}	
	d_{drill}	
	Groundwater pathway	
	$2B_{Culebra}$	Continued support for field tracer test to evaluate best conceptual model
	$k_{\mathbf{x}\text{-}bore}$	
	Culebra, transmissivity index ($\mathfrak{I}_{index}$)	
	S_{PuIV}, S_{PuV}	Made plans to include the influence of attachment of actinides on colloidal material
	$k_{\mathbf{x}\text{-}halite}$	
	$k_{\mathbf{x}\text{-}MB}$	Made plans to model increased permeability from fracturing of the marker bed
	Kd_{Pu}, Kd_{Am}, Kd_U	
	Initial saturation of waste(s_{waste})	

In preparation for PA 1991, the WIPP Project continued to improve modeling of the (1) uncertainty in the brine flow within the Culebra by improving the description of the transmissivity field ($\Im_K$) (where transmissivity is the product of the strata thickness and hydraulic conductivity and where hydraulic conductivity is related to the permeability), and (2) uncertainty of transport properties in the Culebra. The importance of the adsorption distribution coefficient (Kd_e) provided some additional motivation for this improvement.

The low permeability of the salt, uncovered in 1986, did not allow gas to dissipate into the salt and, thus, necessitated modeling multiphase processes within repository. Software development was initiated when commercially available codes did not perform adequately. Also, a gas generation submodel was planned to account for gas generated by the anoxic corrosion of metals and the degradation of organic material in the waste.

1991 WIPP PA

For the 1991 WIPP PA, 335 parameters wee tracked in the analysis, of which 118 were assigned distributions. The uncertainty in transmissivity ($\Im_K$) in the Culebra was based on measurements from 41 wells and described using 60 stochastically generated transmissivity fields from a suite of codes. The 60 transmissivity fields were randomly sampled based on estimated travel time of actinides in the Culebra. Of the 46 parameters whose uncertainty was propagated through the 1991 PA (Helton et al. 1993), the important parameters were the intrusion rate (λ_{drill}), borehole drill diameter (d_{drill}), solubility of individual radioisotopes, (S_e), borehole permeability ($k_{\text{x-}bore}$), halite permeability ($k_{\text{x-}halite}$) (which influence fluid flow from the Salada halite into the repository), and adsorption partition coefficients of individual elements (Kd_e) (Table 1).

The importance of inadvertent human intrusion parameters supported continued improvement to modeling of cuttings and cavings entering a drill hole. In addition, two alternative conceptual models of radioisotope transport in the overlying brine aquifer in Culebra Member of Rustler Formation were run in combination with no sorption of radioisotopes and extremes of climate variability on flow (Helton et al. 1995): (1) dual permeability model in overlying brine aquifer; (2) fracture permeability model in overlying brine aquifer; (3) dual permeability and no retardation; and (4) dual permeability, and extremes of climatic variability. The large variation in results with the chosen model form for actinide transport prompted the WIPP Project to begin discussing a tracer test to select the most appropriate conceptual model.

1992 WIPP PA

In the 1992 PA, three alternative conceptual models were used for evaluating transport of radioisotopes in the Culebra (i.e., fracture only transport, fracture transport with matrix diffusion, fracture transport with clay lining fracture to reduce matrix diffusion, and chemical retardation in the fracture and/or matrix). The effects of implementing, and potential controversy surrounding, these latter alternatives were great enough that they were studied one at a time and all their combinations were run (1) with and without retardation, (2) with and without clay lining fractures, and (3) with and without matrix diffusion. The results were presented individually. A field tracer experiment was executed to evaluate the most appropriate model. For the PA for the CCA in 1996, results of field experiments could be used to select the most appropriate model: fracture transport with matrix diffusion and with some chemical retardation).

There were 310 parameters tracked, of which 93 were assigned a distribution. Many of the parameter ranges and values remained unchanged between the 1991 and 1992 PAs, and only subtle changes occurred in the distributions. The uncertainties of 49 parameters were propagated through the analysis. Generally, the same parameters important in the 1991 PA were important in the 1992 PA (λ_{drill}, d_{drill}, S_e, $k_{\text{x-}bore}$, $k_{\text{x-}halite}$, and Kd_e) (Table 1). However, the permeability of the marker beds ($k_{\text{x-}MB}$) within the host Salado salt formation, was an important parameter and prompted improved modeling of fracturing of the marker beds from elevated pressures within the repository for the CCA PA in 1996. Also, two newly identified important parameters were associated with the Culebra: the fracture spacing ($2B$) and the index parameter for selecting transmissivity fields ($\Im_{index}$) (both of which influenced actinide transport in the brine aquifer). Because of continued importance of direct releases through the intrusion borehole, initiated development of models to include spalling of pressurized waste into the borehole, possible release of contaminated brine.

Beginning in 1994, an effort was made to combine the PA process directly with decision analysis in order to more definitively determine the best combination of scientific investigations, engineered alternatives, and waste acceptance criteria to support the Compliance Certification Application (CCA). The first attempt, called the System Prioritization Methodology (SPM), began in March 1994. The calculations and decision analysis were completed that December (Helton et al. 1997a; 1997b). A second iteration of the methodology was conducted in 1995 (Prindle et al. 1996). The new process produced additional information and thus helped the DOE to allocate resources in 1995 (specifically, research on transport of actinides via colloids). However, the SPM cost much more in time and money than a general sensitivity analysis and the additional information it supplied mainly confirmed earlier sensitivity studies. However, such an undertaking would probably be more successful today in providing additional information because of improved computational capabilities over the past 16 years.

Assessment of CO_2 Leakage into Overlying Aquifer and Probability Monitoring Detects Leakage

As an example, we examine liquid CO_2 injection into a brine filled horizon and the risk of CO_2 leaving the injection horizon and migrating through an existing leaky borehole into an overlying aquifer. Several analytical solutions are coupled with some simplifying assumptions to model CO_2 injection and leakage through an existing well. Uncertainty in rock properties including the permeability and porosity of the injection horizon as well as the thicknesses of the caprock and of the overlying horizon is addressed through Monte Carlo sampling of these parameters.

Injection of CO_2

In this example, CO_2 is injected as a supercritical liquid through a single well into a permeable horizon filled with brine. The radius of the resulting plume of CO_2 at time t is determined by

$$r = \sqrt{\frac{\mu_w V}{\mu_c B \phi \pi}} \tag{1}$$

where μ_w and μ_c are the viscosities of the brine and the CO_2, respectively, $V(t)$ is the volume of CO_2 injected up to time t and B and ϕ are the thickness and porosity of the injection horizon. Equation 1 is simply the radial displacement in a porous media modified by the square root of the viscosity ratio to account for the two different liquids. Buoyancy effects will cause the assumed sharp interface between the liquids to have a thin leading edge of CO_2 at the top of the horizon (Norbotten et al., 2005; Mathias et al., 2009). This solution assumes that gravity is not a significant factor, which would be an appropriate assumption for a thin injection horizon, large injection rate, and low permeability of the injection horizon.

For any distance, r, from the injection well, the change in horizon pressure over time is calculated using a relatively recent analytical solution (Mathias, et al., 2009, Equations 35, 36, and 37). This approach employs the method of matched asymptotic solutions to calculate both the height of the CO_2-brine interface and the change in pressure from initial conditions for any location at a distance r from the injection well and for any time. The position and time are combined into a single dimensionless parameter using a similarity transform: $x = r_D^2/t_D$ where $r_D = r/r_w$ and $t_D = M_0 t/(2\pi\phi B r_w^2 \rho_c)$, where r_w is the radius of the injection well (L), M_0 is the rate of mass injection (M/T), and ρ_c is the density of CO_2 (M/L^3).

Given a pressure history at the location of the leaking well, the volumetric leakage rate for a given time period, $Q_L(t)$ can be calculated using (Norbotten et al., 2005):

$$Q_L(t) = -(\pi r_w^2) k_L \lambda_c \left[\frac{\Delta P(t)}{B_{cap}} + \rho_c g \right] \tag{2}$$

where k_L is the permeability of the leaking well (L^2), λ_c is the mobility of the CO_2 (ratio of the relative permeability to the viscosity of the CO_2 (LT/M), and B_{cap} is the thickness of the caprock thickness (M). Here we make the simplifying assumption that the plume thickness is 100% of the injection horizon at the time of the start of the leak and that only CO_2 leaks through the borehole (i.e., no brine enters the leaking well—see Nordbotten et al., 2005 for an approach to modeling both CO_2 and brine leakage).

These two equations provide the solution for the amount of CO_2 coming out of a given leaky well. An implicit assumption for this example is that the leakage from a single well does not impact the overall pressure distribution of the plume (i.e., the leakage volume is small relative to the plume volume). More complex and physically realistic treatments of the impact of multiple leaking wells on the pressure distribution and leakage rates are available (Nordbotten et al., 2005; 2009).

Evaluating Implications of Uncertainty

Two classes of uncertainty complicate the calculations of a CO_2 risk assessment and they are labeled here as: epistemic uncertainty and spatial/aleatoric uncertainty. The epistemic uncertainty captures uncertainty in the geologic disposal system into which the CO_2 injection is being completed (e.g., permeability, porosity, unit thickness and spatial extent). Other epistemic uncertainties that might arise in modeling CO_2 injection include the fluid properties (viscosity and density) that are dictated by the potentially uncertain fluid temperatures. The latter spatial/aleatoric uncertainty captures uncertainty in the spatial distribution of existing wells and the subset of those existing wells that are potential leaky wells. More generally, spatial/aleatoric uncertainty could capture information on the spatial distribution of any defects, natural or manmade, and their propensity to conduct CO_2 through the caprock barrier. Here we include the density and locations of the monitoring well network within the overlying aquifer as part of the spatial/aleatoric scenario. Although not uncertainty but rather a monitor option, we also include the percentage of wells that are monitored. Other spatial/aleatoric uncertainties that might arise in modeling CO_2 injection include the rate of CO_2 injection.

In this example, epistemic uncertainty is limited to five parameters; other potential epistemic parameters are fixed as certain (Table 2). Both permeability and porosity are drawn stochastically and a linear correlation coefficient of 0.70 is imposed on the relationship between them. The permeability of the leaky well is set at 100 times that of the injection horizon permeability. The thickness of the injection horizon is considered known at 125 m and the caprock thickness is randomly assigned to be between a factor of 0.25 and 1.25 of the thickness of the injection horizon. Both the injection well and the leaky well have a radius, r_w, of 0.15 m.

Table 2. Epistemic geologic parameters and their distribution types

Geologic Unit	Parameter	Mean/Min	Standard Deviation/Max	Distribution
Injection Horizon	Porosity	0.12	0.03	Normal
	Permeability (m^2)	-14	0.50	Lognormal
	Thickness (m)	125	-	Constant
Caprock	Thickness (m)	31.25	156.25	Uniform
	Well Permeability (m^2)	-12	0.50	lognormal ; correlated to injection horizon permeability
Overlying Aquifer	Porosity	0.12	0.03	Normal
	Thickness (m)	30.0	-	Constant

Spatial/aleatoric uncertainty impacts the density of wells within the injection area as well as the percentage of those wells that are potentially leaking wells. The locations of existing wells and those that are potential leaking wells are modeled as stochastic point processes. The different values of the well densities and percentage of wells that could leak are shown in Table 3. For comparison, the density of wells in the Alberta Basin is at least 0.48 km^{-2} (Watson and Bachu 2007), and in oil producing areas of California, well densities range from 1.0 to 244 km^{-2} (Jordan and Benson, 2009). The reported percentages of existing wells that leak range from less than 1% to as much as 10% (Watson and Bachu 2007). For these analyses, the leak percentage is fixed at 2.5%.

Table 3. Spatial/aleatoric parameters and values examined.

Scenario	Well Density (no./km^2)	Percentage Leaking	Percentage Monitored
1A	0.5	2.5	1.0
1B	1.0	2.5	1.0
1C	5.0	2.5	1.0
1D	10.0	2.5	1.0
2A	0.5	2.5	5.0
2B	1.0	2.5	5.0
2C	5.0	2.5	5.0
2D	10.0	2.5	5.0

Modeling Approach

For each scenario studied, CO_2 is injected into a single well at 60 kg/sec for a period of 50 years. One thousand unique samples are drawn from the fixed and sampled input parameters defining the epistemic geologic uncertainty. The injection occurs into a relatively shallow horizon and the fluid densities and viscosities are assigned to represent values for this depth (i.e., the shallow scenario of Mathias et al., 2009). The plume size at the end of 50 years is calculated and the number of wells intersected by the plume is also calculated for each combination of plume size and well density considered as part of the spatial/aleatoric uncertainty.

For each calculated plume size and geometric parameters, the probability of not intercepting a leaky well is calculated. The hypergeometric distribution provides the probability of having x leaky wells from a total of X wells intercepted, given that M is the size of the total population of wells (number of wells in the entire extent of the injection horizon) within which there are believed to be a total of m leaky wells. The probability of not intercepting a leaky well (x=0) is $\wp\{no\_detect\} = H(0; M, X, m)$. The probability of intercepting one or more leaky wells is the complement: $1.0 - \wp\{no\_detect\}$.

For the cases where the plume intercepts more than one leaky well, we limit the analysis to consideration of a single leaking well during the period of CO_2 injection. However, it cannot be assumed that the leaky well chosen is the closest of the leaky wells to the injector. Therefore, the value of k to define the k^{th} leaky well is selected randomly from the total number of leaky wells intercepted. After this selection, the cumulative distribution function (CDF) of the k^{th} nearest neighbor (*kNN*) distances is calculated (Cressie, 1993; §8.4) and a distance to the leaky well is drawn randomly from this distribution.

Given the distance to the leaky well, the time it takes for the fully saturated thickness of the plume to reach that well is calculated by rearranging Equation 1. This time defines the start of the leak.

The time varying increase in pressure at the leak location is obtained from Mathias et al. (2009, Equations 35, 36 and 37). Assuming heads due to hydrostatic conditions prior to injection of the CO_2, the change in pressure between those two points is due solely to the CO_2 injection. This pressure change is applied as $\Delta P(t)$ in Equation 2 and combined with the well and fluid properties and the thickness of the caprock to determine the leakage rate for each time step. For each parameter set that has a leaky well, the maximum pressure change and the maximum leakage rate across all times in which the leak is active are recorded.

The CO_2 leaks into the overlying aquifer and the plume radius and plume size at the end of the injection period are calculated for the upper aquifer. Similar to the process for the original plume within the injection horizon, the number of wells intercepted by the secondary plume in the overlying aquifer is determined. In the overlying aquifer, the hypergeometric distribution is used again to determine the probability that none of the intercepted wells are monitoring wells, $\wp\{no\_detect\}$ and, conversely, that one or more of the intercepted wells is a monitoring well, $\wp\{detect\}$. A detection of the plume in the overlying aquifer is defined as one or more monitoring wells within the plume extent at the end of the injection period.

Example Results

From this set of simulations, a number of intermediate and final results are available. The results of main interest here are the probability of a leak and the times to beginning of the CO_2 leak. The relationships between the stochastically drawn input values: permeability and porosity of the injection horizon, cap rock thickness, well permeability and porosity of the overlying aquifer and the outputs are also examined. In addition, results of the monitoring program are evaluated by comparing the probability of detecting a leak across the different scenarios.

Figure 2 shows the CDF's of the times to the start of a leak (left image) and the probability of a leak occurring. Increases in the densities of existing wells have a strong impact on both results, especially the probability of a leak. The times to the start of a leak are similar across the scenarios for short times with separation of a factor of 2 in the time to leak for longer times. Low well densities, such as would occur for deep injection horizons, produce longer times to the start of leakage. For each parameter vector considered, the probability of a leak occurring is calculated and the resulting values for those vectors with $\wp\{leak\} > 0$ are shown on the right image. For scenarios 1C and 1D, the well densities are high enough that all vectors produce a $\wp\{leak\}$ value of 1.0. Scenarios 1A and 1B result in $\wp\{leak\}$ values that are still high, > 0.70 for all vectors, but not fixed on 1.0.

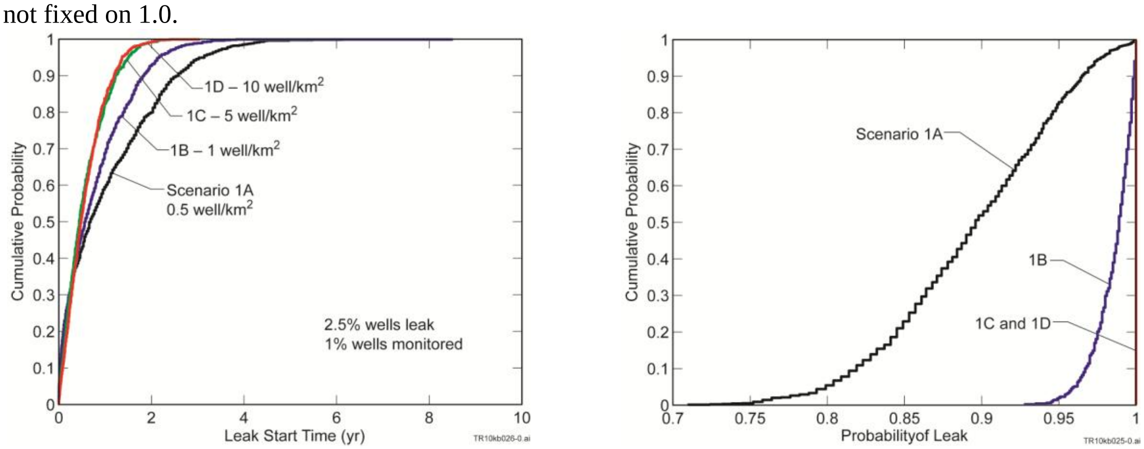

Figure 2. Resulting CDFs of the time from start of injection to start of leak (left) and the probability of a leak occurring (right). Each CDF is constructed from 1000 samples.

Various forms of sensitivity analyses can be applied to the results of the stochastic modeling to better understand the relationships between uncertain input parameters and resulting outputs. Here, the relationship between the porosity and permeability values and the sizes of the primary plume in the injection horizon and the secondary plume in the overlying aquifer are examined visually (Figure 3).

Figure 3 clearly demonstrates the strong relationships between the porosity in the injection horizon and the size of the plume in the same horizon. This result is expected as the calculation for the plume size (Equation 1) contains an inverse relationship between the square of the plume radius the porosity of the horizon. Plume size is not a direct function of the horizon permeability (middle plot, bottom row of Figure 3). However, the horizon permeability does control the timing and magnitude of the pressure change at distances away from the injection well and this exerts control on the amount of CO_2 that can leak out of the horizon into the overlying unit and thus controls the size of the plume in that unit (middle plot, upper row of Figure 3).

Currently, there is no regulatory framework for permitting CO_2 sequestration sites; however, long-term monitoring will likely be a component of this regulatory framework. Probabilistic performance assessment calculations can provide insight into designing effective monitoring programs for CO_2 sequestration. Figure 4 shows results of the probability of detection for Scenarios 1C and 2C as complementary CDFs in log10 space. The Y axis of the complementary CDF is simply 1.0-CDF. Scenario 1C has monitoring at 1% of all wells and Scenario 2C increases the density of the monitoring to 5% of all wells. A perfect monitoring system would produce results that plot in the upper right corner of Figure 4: 100% of all results (CCDF value of 1.0 (or 0.0 in log10 space) would have a $\wp\{\text{detect}\}$ of 1.0 (or 0.0 in log10 space).

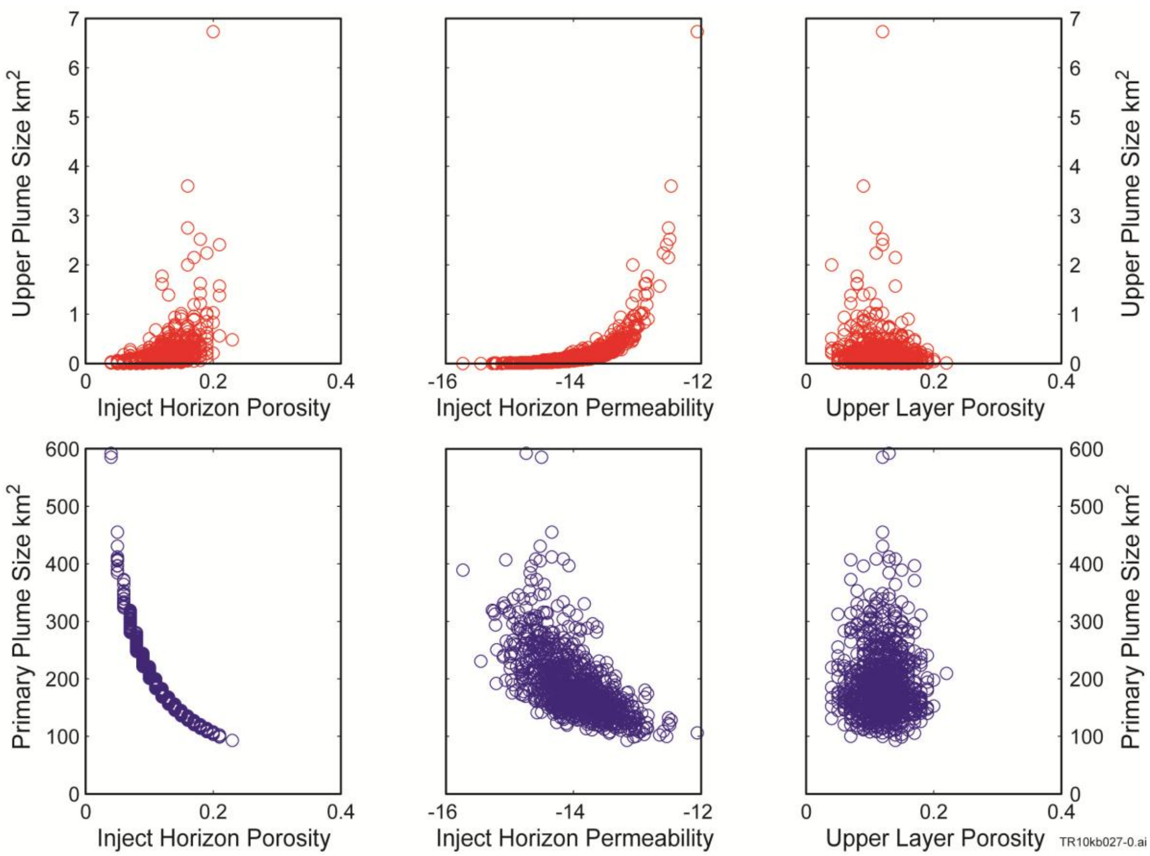

Figure 3. Scatter plots showing the relationship between uncertain epistemic geologic parameters and the resulting plume sizes in the overlying aquifer (top row) and in the injection horizon (bottom row) for Scenario 1C.

Figure 4 illustrates some interesting results. The Y axis value of 10^{-2} defines the threshold where 99% of the results are above that value. For Scenario 1C, there is a 0.99 probability of detection being less than 0.07 ($10^{-1.15}$). Moving across the figure, Scenario 2C has a 0.99 probability of detection being less than 0.32 ($10^{-0.5}$). For a 0.99 probability threshold, a 4% increase in monitoring density increases the probability of detecting the leak by 25%. Alternatively, if the monitoring goal is to provide at least a probability of 0.10 of detecting the plume ($10^{-1.0}$ on the X-axis), Scenario 1C will meet that goal with less than 0.01 probability while Scenario 2C meets the same goal with 0.10 probability.

Summary: Benefits of Using a Risk Assessment Framework

In general, a risk assessment process provides a solid foundation and readily adaptable framework for evaluating the risks of CO2 sequestration. Using risk assessment as the hub for decisions related to CO_2 sequestration in geologic formations has several benefits. First, a risk assessment provides a logical framework for organizing the information relevant to risks to CO_2 sequestration in geologic formations. Second, a probabilistic risk assessment quantitatively considers the uncertainty in the information. Third, the risk assessment for CO_2 provides a means to analyze how different components (reservoir, injection and abandoned wells, and migration pathways) of the disposal system behave in conjunction with each other. A risk assessment can readily identify components of the system that contribute most to the risks and identify areas of research that should be conducted to reduce these risks. Therefore, the results of a risk assessment provide a means to prioritize future data, modeling, and monitoring needs. An ancillary benefit of a risk framework is that analysis process and any decisions based on the analysis are more transparent and traceable and thus more readily scrutinized by peers and regulatory agencies and reviewed by the courts.

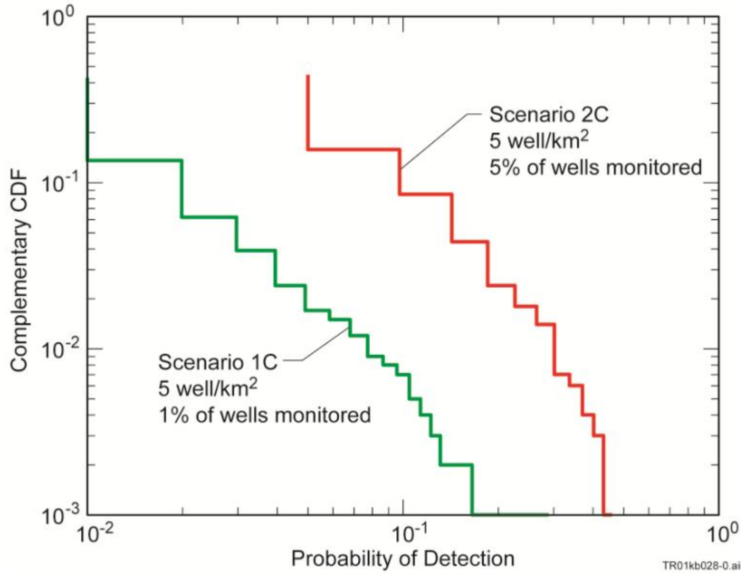

Figure 4. CCDF of detection probability for two different scenarios.

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